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Young radio sources: From newly born to short-lived objects

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Abstract

The evolutionary stage of a powerful radio source originated by an active galactic nucleus is related to its linear size. Following the evolution models, intrinsically compact objects would evolve into the population of classical radio galaxies. However, the fraction of young radio sources in flux density-limited samples is much larger than what is expected from the number counts of large radio sources, suggesting the existence of short-lived objects. We present results of multi-epoch very large array and very long baseline array observations of a sub-sample of extreme GPS sources that should be at the very beginning of their radio evolution. We also briefly introduce a new project aiming at determining the incidence of short-lived objects among a statistically complete sample of young radio sources.

KEYWORDS

radiation mechanisms: non-thermal, galaxies: active, radio continuum: general

1 | INTRODUCTION

Despite decades of efforts, the mechanisms governing the different evolutionary phases of the radio emission in a jetted active galactic nucleus (AGN), from the onset to the fading stage, are still far from being satisfactorily understood. Compact symmetric objects (CSOs) are extragalactic radio galaxies whose radio emission is thought to be in an early evolutionary phase (Wilkinson et al. 1994). Their main characteristics are the steep spectrum ($\alpha > 0.5$; $S_\nu \propto \nu^{-\alpha}$) that turns over at low frequencies, and the intrinsically compact linear size (LS < 15–20 kpc) that makes the radio emission completely embedded within the host galaxy. Estimates of radiative, kinematic, and dynamical ages range from 10^2 years for the most compact (pc-scale) objects to 10^6 years for those with linear size of about 10–20 kpc, supporting the youth scenario (e.g., Dallacasa et al. 2021; Giroletti & Polatidis 2009; Gugliucci et al. 2005; Murgia et al. 1999).

A statistically complete sample of newly born sources is crucial to investigate how the radio emission evolves soon after its onset. The empirical anticorrelation found between the peak frequency and the linear size indicates that the youngest radio sources should be sought among objects whose synchrotron spectrum peaks at a few GHz or beyond (O'Dea & Baum 1997). The selection of radio sources with an inverted spectrum in the GHz regime proved to be highly contaminated by blazars that may match the selection criteria during a particular phase of their typical variability (e.g., Hovatta et al. 2008; Orienti et al. 2007; Torniainen et al. 2005). Unveiling the presence of impostors in order to have clean samples of CSOs is therefore a pivotal work.

Significant variability is not a prerogative of blazars, but very young CSOs may show significant spectral and flux density changes. However, blazars and CSOs are expected to show different types of variability: Erratic for the former, and consistent with adiabatic expansion for the latter. Further information on the nature of the radio emission arises from the pc-scale morphology: CSOs usually display a two-sided structure dominated by steep-spectrum mini-lobes/hotspots, while blazars usually have a core-jet structure dominated by flat-spectrum emission.

In this contribution, we present results on multi-epoch very large array (VLA) observations of a sub-sample of CSO candidates from the faint sample of high-frequency peakers (HFP; Stanghellini et al. 2009). Multifrequency radio data spanning more than a decade allow us to study the long-term variability of these sources and distinguish genuine CSOs from contaminant blazars. VLA data are complemented by very long baseline array (VLBA) observations to constrain the pc-scale structures.

In this contribution, we assume the following cosmology: $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$ in a flat Universe. The spectral index α is defined as $S_\nu \propto \nu^{-\alpha}$.

2 | SPECTRAL VARIABILITY AND RADIO MORPHOLOGY

For 35 out of the 61 sources from the faint HFP sample, we performed multi-epoch observations from 1998 to 2012, allowing us to investigate variability over a time baseline longer than a decade. Each observing run was carried out at several frequencies between 1 and 22 GHz, enabling a quasi-simultaneous determination of the spectral shape in the radio band. The comparison of the peak frequency, spectral slope, and flux density at different epochs is key to determine the type of variability (if any) displayed by the source. Homogeneous synchrotron sources in adiabatic expansion are expected to show (i) a decrease of the flux density in the optically thin part of the spectrum; (ii) a flux density increase in the optically thick part of the spectrum; (iii) a shift toward low frequencies of the spectral peak. On the contrary, blazars are expected to have a random variability with low-activity phases (characterized by flat spectra) interleaved by high-activity/flaring episodes (characterized by convex/inverted spectra).

Among the 35 sources analyzed in this work, we find 6 objects changing the spectral shape from convex during the first epoch of observations, to flat in 2012. The other sources keep the spectral shape, though with some flux density variability (usually about 30%), with the exception of only one object whose variability is below 10% between 1998 and 2012 (see Orienti & Dallacasa 2020 for more details on the variability analysis).

In 18 objects, the changes that we observe are in agreement with a source in adiabatic expansion, while the remaining 16 objects have random variations as expected in blazars. In all the sources consistent with adiabatic expansion the peak frequency is constant (within the errors) or slightly decreases, as expected (Orienti & Dallacasa 2020). Examples of spectra of different types of sources are reported in Figure 1.

Concerning the radio morphology on pc-scale, 11 sources with VLBA observations show a double structure, consistent with a scaled-down version of the classical radio galaxies (Orienti & Dallacasa 2020). However, only in one source we identify the core component (Orienti & Dallacasa 2012). The remaining sources are either unresolved or show a core-jet structure.

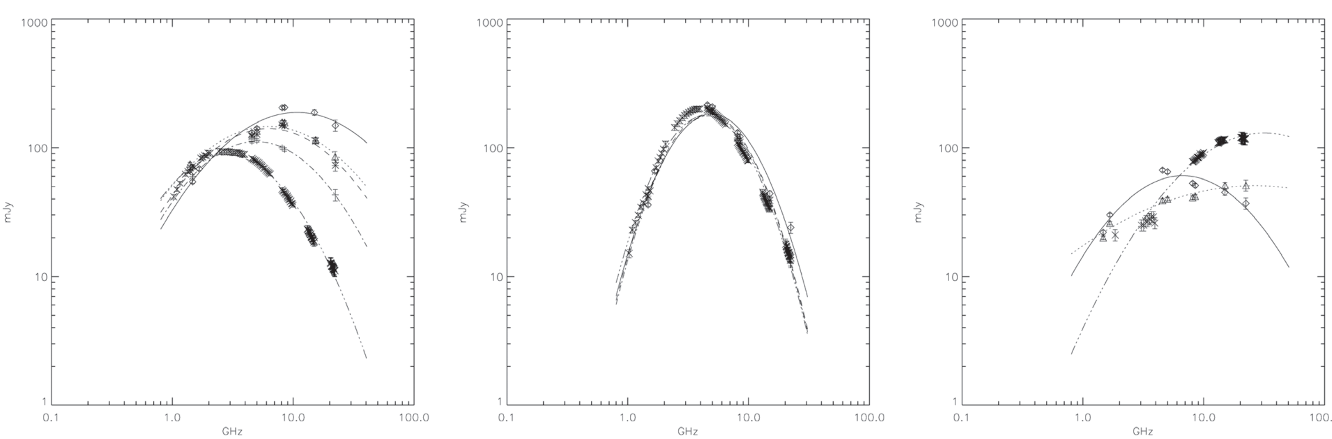

FIGURE 1 Examples of radio spectra (*x*-axis: frequency in GHz, *y*-axis: flux density in mJy) of (*left*) a radio source whose variability is consistent with adiabatic expansion; (*center*) a radio source with variability <30%; (*right*) a radio source with an erratic variability, typical of blazars. Diamonds and solid lines refer to observations in 1998–2000; triangles and dotted lines refer to observations in 2003; asterisks and dashed lines refer to observations in 2004; + signs and dashed-dotted lines refer to observations in 2006/2007; crosses and dashed-three-dotted lines refer to observations in 2012. Adapted from Orienti & Dallacasa (2020)

More information on the variability and morphology studies can be found in Orienti & Dallacasa (2012, 2020).

3 | DYNAMICAL AGES

For those sources consistent with adiabatic expansion, we estimate the dynamical age by:

$$S_1 = S_0 \left(\frac{t_0 + \Delta t}{t_0} \right)^3, \tag{1}$$

where S_0 and S_1 are the flux density in the optically thick regime at the time t_0 (the age of the radio source at the time of the first observation) and $t_0 + \Delta t$, respectively, and Δt is the time elapsed between the observing runs (e.g., Orienti & Dallacasa 2020). If in Equation (1) we consider the flux density at 1.4/1.7 GHz measured at the different epochs, we estimate dynamical ages between 40 and 270 years for 11 sources, indicating that they are at the very beginning of the radio source evolution. We notice that these numbers are highly affected by uncertainties, providing an estimate of the order of magnitude rather than the precise age. For the remaining seven sources, the variations in the optically thick part of the spectrum are consistent within the uncertainties preventing us from obtaining any estimate of the source ages.

For the sources with known redshift and resolved with pc-scale observations we estimate the expansion velocity:

$$v_{\rm exp} = \frac{\theta D_{\rm L}}{(1+z) t_{\rm age}}, \tag{2}$$

where θ is the angular size, $D_{\rm L}$ is the luminosity distance, z is the redshift, and $t_{\rm age}$ the source dynamical age estimated using Equation (1). We obtain expansion velocities between 0.1c and 0.7c, in agreement with the values obtained for other CSOs (e.g., An & Baan 2012). As in the case of the dynamical ages, these estimates are affected by large uncertainties and they provide only the order of magnitude of the expansion velocity.

The sources showing a fast evolution of the spectrum, though still in agreement with adiabatic expansion, should not be the progenitors of classical powerful radio galaxies. In fact, if we consider the shift of the spectral peak with time we find:

$$\frac{\nu_1}{\nu_0} = \left(\frac{t_0}{t_0 + \Delta t} \right)^4, \tag{3}$$

where ν_0 and ν_1 are the peak frequencies at the time t_0 and $t_0 + \Delta t$ (e.g., Orienti & Dallacasa 2020). It is clear that as Δt gets closer to t_0, the peak frequency decreases by a factor of 16, falling in the MHz regime. Moreover, if we consider the optically thin part of the spectrum, the flux would decrease by:

$$\frac{S_1}{S_0} = \left(\frac{t_0 + \Delta t}{t_0} \right)^{-2\delta}, \tag{4}$$

where S_0 and S_1 are the flux densities at the time t_0 and $t_0 + \Delta t$, respectively, while δ is the slope of the electron energy distribution ($\delta = 2\alpha + 1$). If we assume a typical value for δ between 2 and 3, we find that the flux density drops by a factor of 16–60, falling at sub-mJy level (Orienti & Dallacasa 2020). It is possible that these fast-evolving sources may be either the progenitors of low-power objects (e.g., Mingo et al. 2019) detectable by low-frequency facilities, like the forthcoming Square Kilometer Array (SKA), or short-lived episodes of radio emission unable to become larger sources (e.g., Nyland et al. 2020). A support to this interpretation is the very steep spectrum $\alpha > 1.0$ observed in several sources.

These results are discussed in more detail in Orienti & Dallacasa (2020).

4 | HUNTING FOR FADERS AMONG CSOS

The existence of short-lived radio sources may provide an explanation to the excess of intrinsically compact radio sources in flux-density-limited samples. Relics of young radio sources are difficult to find and many discoveries were made serendipitously (e.g., Orienti et al. 2010).

To investigate the incidence of young but fading radio sources, we undertake a project aiming at searching for relics among the young radio sources from the B3-VLA CSS sample (Fanti et al. 2001). We selected only those sources with a spectral index $\alpha > 1$ between 4.8 and 8.4 GHz, and without any evidence of an active core in the literature (Orienti et al. 2004; Rossetti et al. 2006). The final sample consists of 18 sources: 6 with largest angular size (LAS) < 0.25 arcsec, and 12 with LAS > 0.25 arcsec.

We observed the six most compact sources with the VLBA at 4.8 and 8.4 GHz, while the remaining sources were observed with the VLA in L, S and U bands. We complemented our new VLA data with archival VLA observations at 4.8 and 8.4 in order to have a well sampled radio spectrum. For 6 out of 12 sources with LAS > 0.25 arcsec we also got e-MERLIN observations with higher angular resolution in L and C bands in order to unveil the presence of a core that may be hidden in the diffuse emission not resolved by VLA data. This is the first systematic work to constrain the percentage of short-lived sources to date. The high-angular resolution of the new data is allowing us to identify the core in some of the sources, whereas in others no active regions can be found. An example of a source

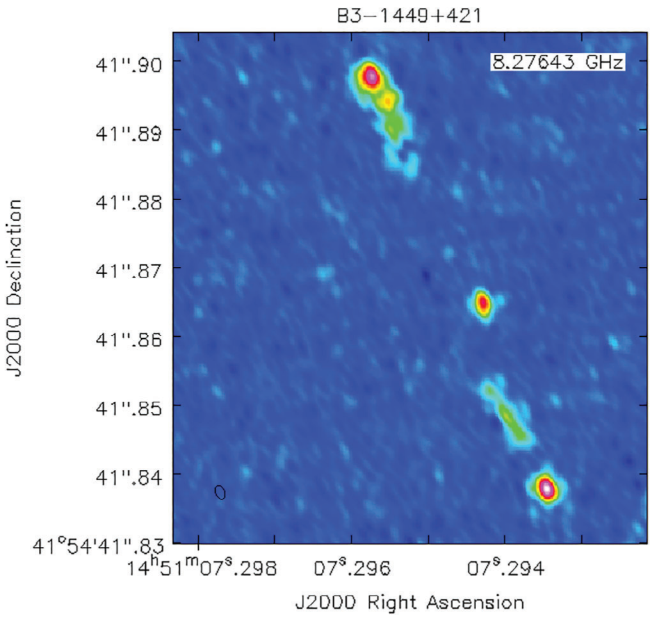

FIGURE 2 Example of a very long baseline array (VLBA) image at 8.3 GHz where we could identify the core component for this source for the first time

where we could unveil the presence of the core is presented in Figure 2.

Results will be presented in a forthcoming paper.

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